

Search for the anomalous electromagnetic moments of the tau lepton through electron-photon scattering at the CLIC

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Abstract

We have examined the anomalous electromagnetic moments of the tau lepton in the processes $e^- \gamma \rightarrow \nu_e \tau \bar{\nu}_\tau$ (γ is the Compton backscattering photon) and $e^- e^+ \rightarrow e^- \gamma^* e^+ \rightarrow \nu_e \tau \bar{\nu}_\tau e^+$ (γ^* is the Weizsacker-Williams photon) with unpolarized and polarized electron beams at the CLIC. We have obtained 95% confidence level bounds on the anomalous magnetic and electric dipole moments for various values of the integrated luminosity and center-of-mass energy. Improved constraints of the anomalous magnetic and electric dipole moments have been obtained compared to the LEP sensitivity.

PACS numbers: 14.60.Fg, 13.40.Gp

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I. INTRODUCTION

The spin and magnetic moment of the electron arise from the aberration of atoms embedded in a magnetic field, in which fine structure is observed by using spectroscopic methods [1, 2]. The magnetic moment of the electron with spin \vec{s} , electric charge e and mass m can be written in the general form as $\vec{\mu} = g(e\hbar/2mc)\vec{s}$, where the coefficient g , being a fine structure constant, is stated as $g \cong 2 [1 + (\alpha/2\pi) - 3.28(\alpha/\pi)^2] \cong 2.0023192$. The g is the Landé g-factor for the electron's spin. The obtainment of $g = 2$ is possible in consideration of the Dirac equation. The deviation from the Dirac value $a_e = (g - 2)/2$ measured by spin precession methods is known as the anomalous magnetic moment. The first detailed investigation on anomalous magnetic moment of the electron was performed within the framework of Quantum Electrodynamics (QED) using radiative corrections by Schwinger in 1948, as $a_e = \alpha/2\pi$ [3]. Ever since, many experimental and theoretical works have been devoted to improve for a -values of particles [4]. It should be noted that the studies on anomalous magnetic moment of particles have provided a precision test of the Standard Model (SM) and gives point of view "new physics" effects [5]. However the anomalous magnetic moment a_μ of the muon is important to examine the SM and in establishing of alternative theories to the SM. While a_e and a_μ can be determined by spin precession experiments the anomalous magnetic moment of the tau cannot be measured by same method due to short lifetime $2.906 \times 10^{-13}s$ of the tau lepton [6]. So, no direct measurement of the tau lepton's anomalous magnetic moment exists up to now. Producing tau lepton is performed by collision experiments with accuracy. The theoretical value of the a_τ from QED by considering higher loop corrections is given as $a_\tau^{SM} = 0.001177$ [7, 8]. The experimental bounds on the a_τ are provided by,

$$\text{L3: } -0.052 < a_\tau < 0.058,$$

$$\text{OPAL: } -0.068 < a_\tau < 0.065,$$

$$\text{DELPHI: } -0.052 < a_\tau < 0.013$$

collaborations at the LEP at 95% C.L. [9–11].

The CP violation effects have important results on the coupling of the tau lepton. K_L^0 mesons enable a perfect experimental system to test CP invariance. A pure sample of the long-lived species can be formed by using a long enough beam. In such a system, if a 2π decay is observed, it is clear that CP has been violated [12]. Here this phenomenon can

be adapted to the SM by including an experimental phase factor to Cabibbo-Kabayashi-Maskawa matrix in the quark sector [13]. However, while there is no question CP violation in the lepton sector in the SM, CP violation in the quark sector leads to form a very small contribution to CP violation of the leptonic interactions via multi-loop effects. At least three-loop are needed to enable corresponding contribution of the SM to the electric dipol moment of the tau lepton, in which estimated value range is obtained as $|d_\tau| \leq 10^{-34} e cm$ [14]. Neutrino mixing with different masses are another source of CP violating in the lepton sector as similar to the CP violation in the quark sector [15].

Additional sources beyond the SM for the CP violation in the lepton sector are leptoquark [16, 17], SUSY [18], left-right symmetric [19, 20] and Higgs-Multiplets [21, 22]. The bounds at the 95% C. L. on the anomalous electric dipole moment of the tau are obtained by the LEP experiments,

$$\begin{aligned} \text{L3: } |d_\tau| &< 3.1 \times 10^{-16} e cm, \\ \text{OPAL: } |d_\tau| &< 3.7 \times 10^{-16} e cm, \\ \text{DELPHI: } |d_\tau| &< 3.7 \times 10^{-16} e cm. \end{aligned}$$

However, the most restrictive experimental bounds are given by BELLE:

$$\begin{aligned} -2.2 &< \text{Re}(d_\tau) < 4.5 \times (10^{-17} e cm), \\ -2.5 &< \text{Im}(d_\tau) < 0.8 \times (10^{-17} e cm). \end{aligned}$$

In this study we have examined the processes $e\gamma \rightarrow \nu_e \tau \bar{\nu}_\tau$ (γ is the Compton backscattering photon) and $e^- e^+ \rightarrow e^- \gamma^* e^+ \rightarrow \nu_e \tau \bar{\nu}_\tau e^+$ (γ^* is the Weizsacker-Williams photon). There are three Feynman diagrams of these processes to be used as mediators W^+, τ, e . $\tau\tau\gamma$ vertex belongs to only a diagram in these Feynman diagrams. The main motivation of the present study is on how to investigate $\tau\tau\gamma$ vertex contribution with anomalous electromagnetic form factors to the SM. In this manner, the electromagnetic vertex factor in characterizing the interaction of tau lepton with photon can be parametrized by

$$\Gamma^\nu = F_1(q^2)\gamma^\nu + \frac{i}{2m_\tau}F_2(q^2)\sigma^{\nu\mu}q_\mu + \frac{1}{2m_\tau}F_3(q^2)\sigma^{\nu\mu}q_\mu\gamma^5 \quad (1)$$

with $\sigma^{\nu\mu} = \frac{i}{2}(\gamma^\nu\gamma^\mu - \gamma^\mu\gamma^\nu)$, where q and m_τ are the photon momentum and the mass of tau lepton, respectively. $F_{1,2,3}(q^2)$ are the electric charge, the anomalous magnetic dipole and

the electric dipole form factors of the tau lepton. As well known, when $F_1 = 1, F_2 = F_3 = 0$, the electromagnetic vertex factor is reduced to vertex factor in the SM. However, due to $\tau\tau\gamma$ vertex, in other words, contributions from loop effects or arising from the new physics, F_2 and F_3 could not be taken as zero [23–25]. When considering the limiting case of $q^2 \rightarrow 0$, the form factors become

$$F_1(0) = 1, F_2(0) = a_\tau, F_3(0) = \frac{2m_\tau d_\tau}{e} \quad (2)$$

in which new case relates to the static properties of the fermions.

On the other hand, it should be noted that the Compact Linear Collider (CLIC) is a collider with the range 0.5 – 3 TeV in order to perform e^+e^- collision that is planned to be constructed at a future date [26]. In this study, as previously mentioned briefly, we have probed the anomalous magnetic and electric dipole moments of the tau lepton by considering at a future linear collider with high-energy and high-luminosity, such as the CLIC [27]. Beam polarization could play essential role in the next linear colliders as well as RHIC and HERA. It is expected that 80 % polarization of lepton beam can be achievable at the future linear colliders [28]. In this work, we take into account one beam can be 80% polarization (-80% means that eighty of percent are left polarized).

In this paper, we have examined the anomalous magnetic and electric dipole moments of the tau lepton through the processes $e^-\gamma \rightarrow \nu_e\tau\bar{\nu}_\tau$ and $e^-e^+ \rightarrow e^-\gamma^*e^+ \rightarrow \nu_e\tau\bar{\nu}_\tau e^+$. Linear colliders can be constructed $\gamma\gamma$ and $e\gamma$ collider modes with real photons. This real photon beam is obtained by the Compton backscattering of laser photons off linear electron beam. Moreover, most of these photon beams can be high energy region [29, 30]. The linear colliders make it possible to $e\gamma^*$ and $\gamma^*\gamma^*$ interactions to examine new physics beyond the SM. The photons which are emitted from the incoming electrons scatter at very small angles from the beam pipe. Therefore, these photons have very low virtuality and we say that these photons "almost-real". These processes take place as follows: Almost-real photons (γ^*) are emitted from the incoming electrons (positrons) and interact other photon or electrons (positrons). Then, the $\gamma^*\gamma^*$ or $e\gamma^*$ interacts with each other to produce X through the subprocess $\gamma^*\gamma^* \rightarrow X$ or $e^-\gamma^* \rightarrow X$. These photon distributions can be examined phenomenologically via the WWA approximation in the literature [36–42, 44–46]. The WWA has simple formulas then it provides to get simple numerical estimations [50]. Moreover, this method gives a facility

in the experiments because it permits to give cross section for the process $e^-\gamma^* \rightarrow X$ approximately through the study of the main $e^-e^+ \rightarrow e^-\gamma^*e^+ \rightarrow Xe^+$ process. Here, X represents particles obtained in the final state. Also, these interactions have a very clean experimental conditions, since they contain only electromagnetic interactions. With these motivations, we have obtained the sensitivity bounds on new physics parameters through the $e^-\gamma \rightarrow \nu_e\tau\bar{\nu}_\tau$ and $e^-e^+ \rightarrow e^-\gamma^*e^+ \rightarrow \nu_e\tau\bar{\nu}_\tau e^+$ in next subsections.

In the next section, we briefly outline of our numerical calculation details and results. Final section is devoted to our summary and conclusions.

II. NUMERICAL ANALYSIS

A. Analysis with Compton Backscattered Photons

In this subsection, we show the numerical results for the $e^-\gamma \rightarrow \nu_e\tau\bar{\nu}_\tau$. All numerical analysis, we have used the CalcHEP package [47, 48]. This program allows automatic calculations of the distributions and cross sections in the SM as well as their extensions at the tree level. We have considered $\sqrt{s} = 1.4$ TeV and 3 TeV CLIC center-of-mass energies in our calculations. We carry out the following cuts on the final state leptons in all of our calculations $|\eta| < 2.5$. In sensitivity analysis, we take into account χ^2 method,

$$\chi^2 = \left(\frac{\sigma_{SM} - \sigma(F_1, F_2)}{\sigma_{SM} \delta_{stat}} \right)^2 \quad (3)$$

where $\sigma(F_1, F_2)$ is the total cross section which includes SM and new physics, $\delta_{stat} = 1/\sqrt{N}$ is the statistical error and $N = \sigma_{SM} \times BR \times L_{int}$. We assume that tau lepton decays into hadrons hence we take $BR = 0.65$ in all calculations.

In Table I, we present the 95% C.L. sensitivity bounds on the anomalous couplings a_τ and d_τ for Compton backscattered photon and unpolarized electron beam ($P_{e^-} = 0\%$), $\sqrt{s} = 1.4$ TeV and $\sqrt{s} = 3$ TeV center-of-mass energies and integrated CLIC luminosities, whereas one of the parameters is taken to be zero at each calculation. It can be understood that the bounds on the anomalous couplings are sensitive to the values of the center-of-mass energy and luminosity. Also, we can see from this table that our bounds on the a_τ are better than the current experimental limits even for $L = 10 \text{ fb}^{-1}$ and $\sqrt{s} = 1.4$ TeV. In Figs. 1 and 2, we show the contour bounds in the plane $F_2 - F_3$ for $\sqrt{s} = 1.4$ TeV with $L = 100, 500, 1500$

fb^{-1} and $\sqrt{s} = 3 \text{ TeV}$ with $L = 100, 1000, 2000 \text{ fb}^{-1}$, respectively. As we can see from these figures, the best bounds on anomalous couplings are obtained for the $\sqrt{s} = 3 \text{ TeV}$ and $L = 2000 \text{ fb}^{-1}$.

Additionally, we have used the polarized electron beam in our analysis. For a process with electron and positron beam polarizations, the cross section can be defined as [49],

$$\sigma = \frac{1}{4}(1 - P_{e+})(1 + P_{e-})\sigma_{-1+1} + \frac{1}{4}(1 + P_{e+})(1 - P_{e-})\sigma_{-1+1}. \quad (4)$$

where σ_{ab} represents the obtained cross section with fixed helicities a for positron and b for the electron. P_{e-} and P_{e+} are the polarization degree of the electron and positron, respectively. In our numerical calculations we take into account only left-handed electrons since the examined process includes only a weak interaction. Hence, we have applied the electron polarization as $P_{e-} = -80\%$. To this purpose, we give 95% C.L. sensitivity bounds on the anomalous a_τ and d_τ couplings in Table II here we have considered $P_{e-} = -80\%$ for $\sqrt{s} = 1.4$ and $\sqrt{s} = 3 \text{ TeV}$ with different luminosity values. As seen from the table obtained sensitivity bounds on the anomalous couplings are better than Table I. In Figs. 3 and 4 for polarized electron beam, we show the contour bounds in the plane $F_2 - F_3$ for the $\sqrt{s} = 1.4 \text{ TeV}$ with $L = 100, 500, 1500 \text{ fb}^{-1}$ and $\sqrt{s} = 3 \text{ TeV}$ with $L = 100, 1000, 2000 \text{ fb}^{-1}$, respectively. Comparison of Figs. 1 (2) and 3 (4) apparently shows that the excluded area of the model $F_2 - F_3$ parameters that we have obtained from the polarized beams ($P_{e-} = -80\%$) extends to wider regions than the cases of the unpolarized electron beams.

B. Analysis with Weizsacker-Williams Photons

We have analyzed the anomalous dipole moments of the tau lepton via the main process $e^-e^+ \rightarrow e^-\gamma^*e^+ \rightarrow \nu_e\tau\bar{\nu}_\tau e^+$ in this subsection. In Table III, we present the 95% C.L. sensitivity bounds on the anomalous a_τ and d_τ parameters for the unpolarized electron beams. We can obtain from the table that the sensitivity bounds of the anomalous couplings enhance with the increasing center-of-mass energy and luminosity. The obtained bounds for the a_τ are also better than the current experimental limits. On the other hand, bounds with Compton backscattered photon (Table I) sensitive than the bounds for Weizsacker-Williams approximation (Table III). Main reason of this situation is the Compton backscattered photon spectrum gives higher effective than the Weizsacker-Williams photon spectrum in

high energy regions [29, 33]. However, the application of the WWA gives a lot of benefits in experimental and phenomenological studies as mentioned in Section I. We present the 95% C.L. sensitivity bounds on the anomalous a_τ and d_τ parameters for the $P_{e^-} = -80\%$ polarized electron beams in Table IV for $\sqrt{s} = 1.4$ TeV with $L = 100, 500, 1500$ fb $^{-1}$ and $\sqrt{s} = 3$ TeV with $L = 100, 1000, 2000$ fb $^{-1}$, respectively. Best bounds on the anomalous couplings have been obtained in this situation as we expected due to above discussions.

In Figs. 5 and 6 for unpolarized electron beam we present the contour bounds in the plane $F_2 - F_3$ for $\sqrt{s} = 1.4$ TeV with $L = 100, 500, 1500$ fb $^{-1}$ and $\sqrt{s} = 3$ TeV with $L = 100, 1000, 2000$ fb $^{-1}$, respectively. Fig.7 (Fig.8) same as the Fig. 5 (Fig.6) but for the polarized electron beams. Limits for polarized case strong compared with unpolarized case, however, that bounds weak compared with the compton backscattered case.

III. CONCLUSION

We have analyzed tau lepton anomalous dipole moments through the processes $e^-\gamma \rightarrow \nu_e \tau \bar{\nu}_\tau$ and $e^-e^+ \rightarrow e^-\gamma^*e^+ \rightarrow \nu_e \tau \bar{\nu}_\tau e^+$. These processes have very clean environment. Therefore, deviation of the anomalous couplings from the expected values of the SM would evidence the existence of the new physics. We have found that $e^-\gamma \rightarrow \nu_e \tau \bar{\nu}_\tau$ process give better bounds than the other. However, the processes which are include $\gamma\gamma$ and $e^-\gamma$ interactions require new apparatus. On the other hand, $e^-\gamma^*$ and $\gamma^*\gamma^*$ are occurred spontaneously without any new apparatus.

Additionally, we have used polarized and unpolarized electron beam in our study. We have seen that the polarization enhances the sensitivity bounds. Our results for the a_τ better than the current experimental limits. Based on the obtaining of this paper, it is concluded that, CLIC provides new opportunities for examination of the tau physics beyond the SM with using $e\gamma$ and $e\gamma^*$ mode.

IV. ACKNOWLEDGEMENTS

This work has been supported by the Scientific and Technological Research Council of Turkey (TUBITAK) in the framework of Project No. 115F136.

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TABLE I: 95% C.L. sensitivity bounds of the a_τ and d_τ couplings for Compton backscattered photon and unpolarized electron beam, various center-of-mass energies and integrated CLIC luminosities.

| $\sqrt{s}(\text{TeV})$ | Luminosity(fb^{-1}) | a_τ | $ d_\tau (e\text{ cm})$ |
|------------------------|-------------------------|---------------------|-------------------------|
| 1.4 | 10 | $(-0.0105, 0.0105)$ | 0.59×10^{-15} |
| | 100 | $(-0.0059, 0.0059)$ | 0.33×10^{-15} |
| | 500 | $(-0.0039, 0.0039)$ | 0.22×10^{-15} |
| | 1500 | $(-0.0030, 0.0030)$ | 0.17×10^{-15} |
| 3 | 10 | $(-0.0046, 0.0046)$ | 0.26×10^{-15} |
| | 500 | $(-0.0017, 0.0017)$ | 0.09×10^{-15} |
| | 1000 | $(-0.0014, 0.0014)$ | 0.08×10^{-15} |
| | 2000 | $(-0.0012, 0.0012)$ | 0.07×10^{-15} |

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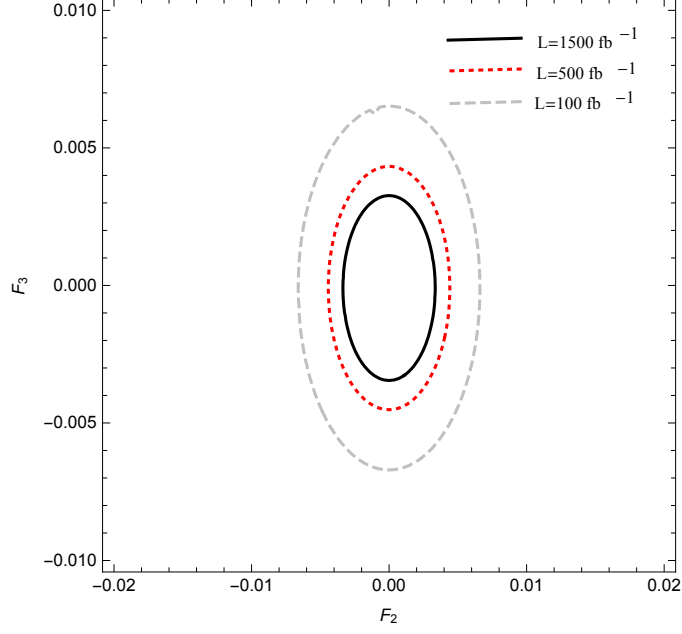


FIG. 1: Limits contours at the 95% C.L. in the $F_2 - F_3$ plane for Compton backscattered photon $P_{e-} = 0\%$ and $\sqrt{s} = 1.4$ TeV.

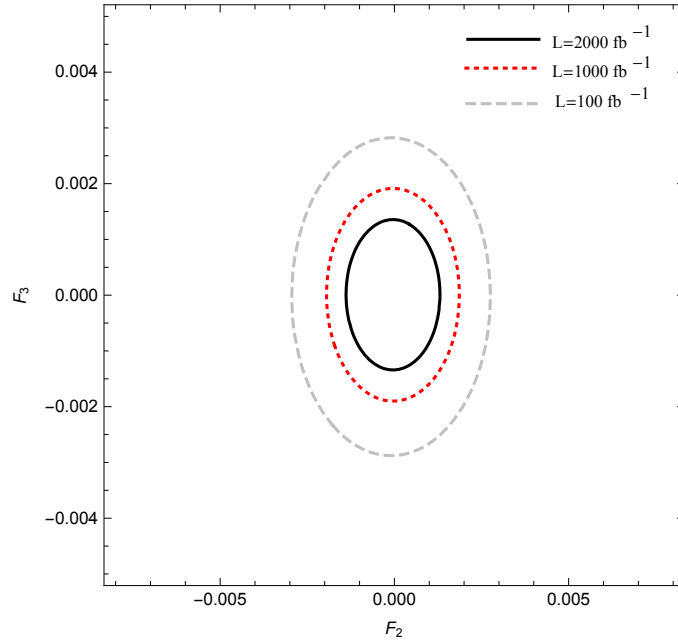


FIG. 2: Limits contours at the 95% C.L. in the $F_2 - F_3$ plane for Compton backscattered photon $P_{e-} = 0\%$ and $\sqrt{s} = 3$ TeV.

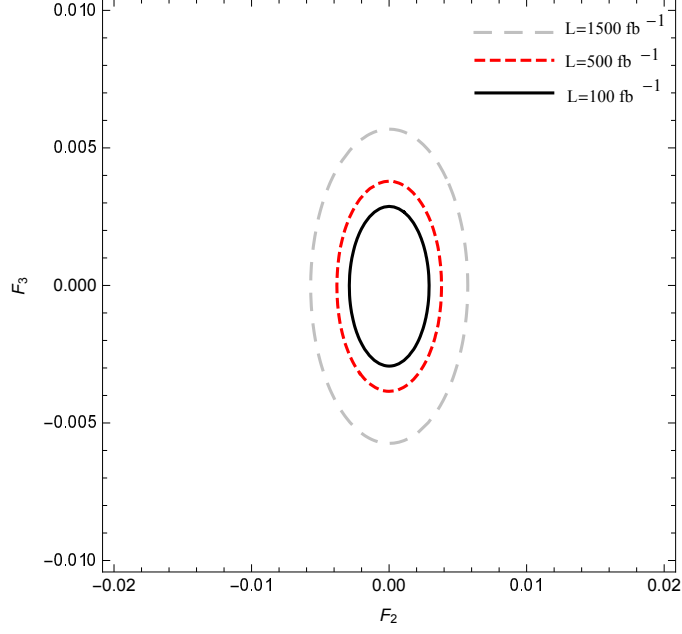


FIG. 3: Limits contours at the 95% C.L. in the $F_2 - F_3$ plane for Compton backscattered photon $P_{e^-} = -80\%$ and $\sqrt{s} = 1.4$ TeV.

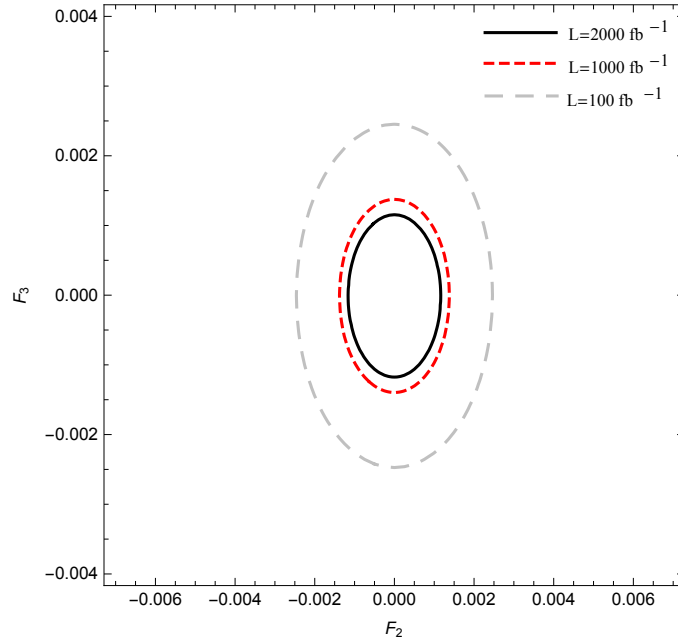


FIG. 4: Limits contours at the 95% C.L. in the $F_2 - F_3$ plane for Compton backscattered photon $P_{e^-} = -80\%$ and $\sqrt{s} = 3$ TeV.

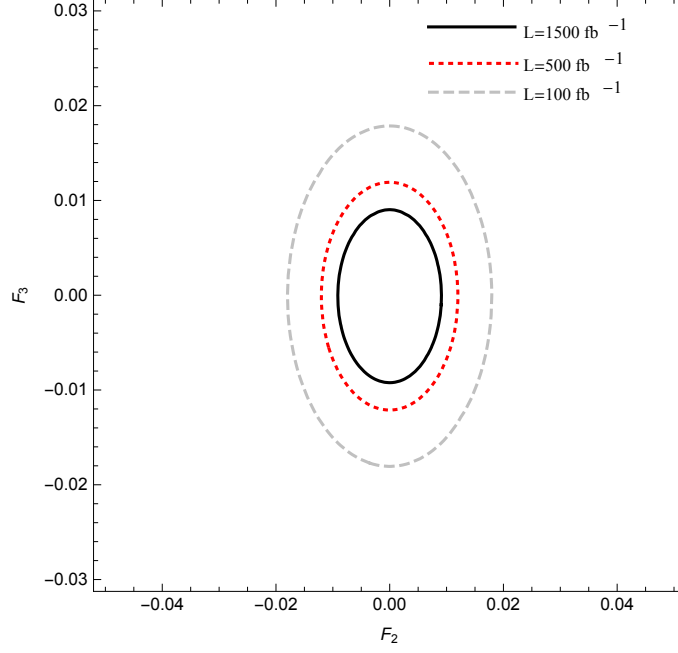


FIG. 5: Limits contours at the 95% C.L. in the $F_2 - F_3$ plane for Weizsacker-Williams photon $P_{e^-} = 0\%$ and $\sqrt{s} = 1.4$ TeV.

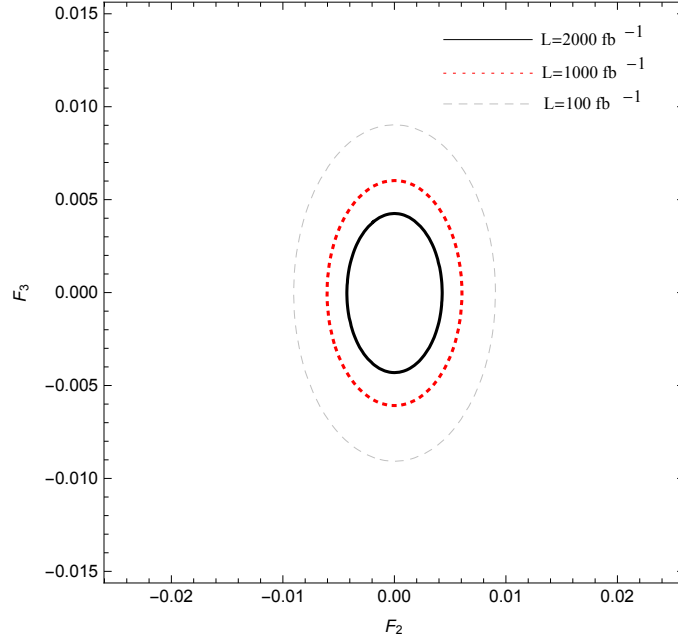


FIG. 6: Limits contours at the 95% C.L. in the $F_2 - F_3$ plane for Weizsacker-Williams photon $P_{e^-} = 0\%$ and $\sqrt{s} = 3$ TeV.

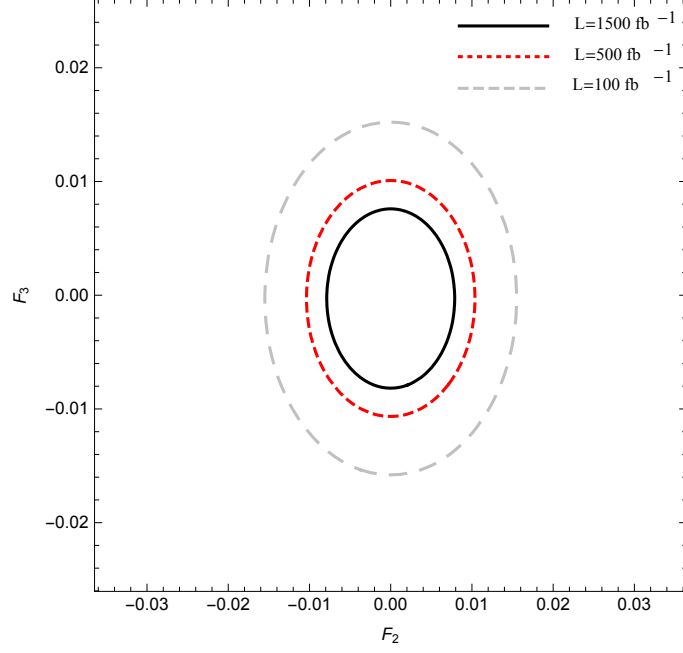


FIG. 7: Limits contours at the 95% C.L. in the $F_2 - F_3$ plane for Weizsacker-Williams photon $P_{e^-} = -80\%$ and $\sqrt{s} = 1.4$ TeV.

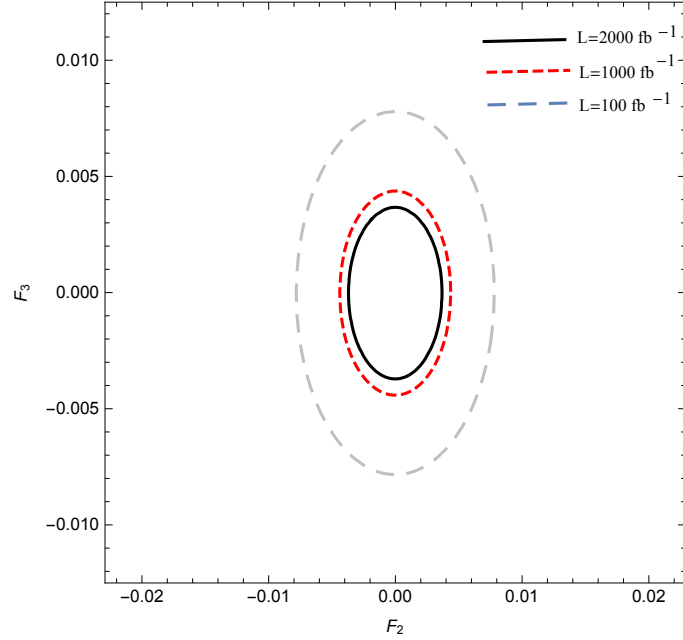


FIG. 8: Limits contours at the 95% C.L. in the $F_2 - F_3$ plane for Weizsacker-Williams photon $P_{e^-} = -80\%$ and $\sqrt{s} = 3$ TeV.

TABLE II: 95% C.L. sensitivity bounds of the a_τ and d_τ couplings for Compton backscattered photon and polarized electron (-80%) beam, various center-of-mass energies and integrated CLIC luminosities.

| $\sqrt{s}(\text{TeV})$ | Luminosity(fb^{-1}) | a_τ | $ d_\tau (e\text{ cm})$ |
|------------------------|-------------------------|---------------------|-------------------------|
| 1.4 | 10 | $(-0.0091, 0.0091)$ | 0.51×10^{-15} |
| | 100 | $(-0.0051, 0.0051)$ | 0.28×10^{-15} |
| | 500 | $(-0.0034, 0.0034)$ | 0.19×10^{-15} |
| | 1500 | $(-0.0026, 0.0026)$ | 0.14×10^{-15} |
| 3 | 10 | $(-0.0039, 0.0039)$ | 0.22×10^{-15} |
| | 500 | $(-0.0015, 0.0015)$ | 0.08×10^{-15} |
| | 1000 | $(-0.0012, 0.0012)$ | 0.07×10^{-15} |
| | 2000 | $(-0.0010, 0.0010)$ | 0.06×10^{-15} |

TABLE III: 95% C.L. sensitivity bounds of the a_τ and d_τ couplings for Weizsacker-Williams photon and unpolarized electron beam, various center-of-mass energies and integrated CLIC luminosities.

| $\sqrt{s}(\text{TeV})$ | Luminosity(fb^{-1}) | a_τ | $ d_\tau (e\text{ cm})$ |
|------------------------|-------------------------|---------------------|-------------------------|
| 1.4 | 10 | $(-0.0287, 0.0285)$ | 1.57×10^{-15} |
| | 100 | $(-0.0162, 0.0160)$ | 0.87×10^{-15} |
| | 500 | $(-0.0109, 0.0106)$ | 0.56×10^{-15} |
| | 1500 | $(-0.0083, 0.0081)$ | 0.41×10^{-15} |
| 3 | 10 | $(-0.0144, 0.0144)$ | 0.79×10^{-15} |
| | 500 | $(-0.0054, 0.0054)$ | 0.29×10^{-15} |
| | 1000 | $(-0.0046, 0.0045)$ | 0.26×10^{-15} |
| | 2000 | $(-0.0039, 0.0038)$ | 0.21×10^{-15} |

TABLE IV: 95% C.L. sensitivity bounds of the a_τ and d_τ couplings for Weizsacker-Williams photon and polarized electron (-80%) beam, various center-of-mass energies and integrated CLIC luminosities.

| $\sqrt{s}(\text{TeV})$ | Luminosity(fb^{-1}) | a_τ | $ d_\tau (e\text{ cm})$ |
|------------------------|-------------------------|---------------------|-------------------------|
| 1.4 | 10 | $(-0.0248, 0.0246)$ | 1.37×10^{-15} |
| | 100 | $(-0.0140, 0.0138)$ | 0.77×10^{-15} |
| | 500 | $(-0.0094, 0.0092)$ | 0.52×10^{-15} |
| | 1500 | $(-0.0072, 0.0069)$ | 0.38×10^{-15} |
| 3 | 10 | $(-0.0124, 0.0124)$ | 0.68×10^{-15} |
| | 500 | $(-0.0046, 0.0046)$ | 0.26×10^{-15} |
| | 1000 | $(-0.0039, 0.0039)$ | 0.22×10^{-15} |
| | 2000 | $(-0.0033, 0.0033)$ | 0.18×10^{-15} |